"MICROGRAVITY SCIENCES APPLICATION VISITING SCIENTIST PROGRAM"

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Submitted to:

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January 10, 1994

QUARTERLY PROGRESS REPORT

MICROGRAVITY SCIENCES APPLICATION VISITING SCIENTIST PROGRAM

CONTRACT NAS8-38785

October 1, 1993 - December 31, 1993

Visiting Scientists and Research Associates

The following Visiting Scientists continued their appointments on this contract during this quarter. They support work on Protein Crystal Growth (PCG) and separation methods used to purify proteins and other biological samples prior to studies such as PCG; solid materials characterization for the electronic materials branch; and research in synthesis and characterization of non-linear optical materials, for the electronic and photonic materials branch.

Dr. Ching-Hua Su, solid materials characterization;
Dr. Joseph Xiao-min Ho, crystal growth;
Dr. Merrill King, combustion study and analysis of various chemical programs;
Dr. Mark Steven Paley, synthesis and characterization of non-linear optical materials;
Dr. Narayanan Ramachandran, fluid dynamics;
Dr. Terry Rolin, characterization of superconductors;
Dr. Yi-Gao Sha, crystal growth;
Dr. Manfred Lichtensteiger, growth and characterization of electronic materials;
Ms. Elizabeth Forsythe, protein solubilities, purification, separation and crystallization;
Mr. Laurent Sibille, protein solution chemistry;
Ms. Pamela Twigg, protein crystal growth;
Mr. Rick McConnell, program management.

1. Activities Performed

Dr. Ching-Hua Su performed the following activities during this reporting period:

- A seeded-growth experiment was prepared which uses a ZnTe seed and a segment of the ingot with compositional profile of the diffusion boundary layer on top of the seed and an ingot of uniform composition of $X=0.16$;
- An ampoule was also prepared for the growth of HgZnTe in an axial magnetic field of 40 kGauss.

Dr. Joseph Xiao-min Ho installed and tested a beta version of software package <HKL> for crystal diffraction data processing. He collected and analyzed data for crystals of HSA and fatty acid complex. The binding loci have also been determined for modelling. He determined the structure of a recombinant glutathion s-transferase (GST) fused with epitope of gp41 of HIV virus and aided in the refinement of this structure.

Dr. N. Ramachandran focused the majority of his time compiling and editing the proceedings for the Joint L+1 Science Review for USML-1 and USMP-1 with the Microgravity Measurement Group. All discussions were transcribed and edited. It is anticipated that the proceedings will be in press by the January, 1994.

LDV measurements in a three dimensional ventilated enclosure were completed. ASME has expressed interest in using the data for benchmarking CFD codes. A copy of the initial data analysis has been forwarded to the benchmark committee for their evaluation and comments. Some additional testing may be required in this regard.

Calibration testing of hot wire anemometers, Cobra probes and 5-hole probes in high Reynolds number flows was completed in a special test section in the Turbine Test Equipment Facility. Data analysis is underway. The setup was also used to test new seeding methods for LDV applications. A new 5 Watt laser was brought on-line and tested with the LDV equipment and dditional tests remain to make the unit fully operational.

Ms. Pamela D. Twigg's research centered on binding chemistry and crystallization studies with albumin complexes. She continued screening crystallization conditions for several proteins related to HIV and HTLV research collaboration and began working with preliminary crystallization screens for flight opportunity in vapor diffusion protein crystal growth hardware.

Dr. Mark Steven Paley's research focused on photo-deposition of polydiacetylene thin films (PDAMNA) from solution has been going extremely well. Recently, a UV laser was demonstrated to be useful to deposit the polymer, thereby making possible the photo-deposition of optical circuits. This could be of great use for making devices such as waveguides and integrated optics; and it could be a significant step towards making the use of polydiacetylenes for NLO applications more commercially feasible. There is one patent application on photo-deposition of PDAMNA from solution in the process at NASA, and there are preparations to submit another on laser-deposition. Also, a paper on vapor deposition of PDAMNA onto ordered polymer surfaces has been published in *Chemistry of Materials*. Dr. Paley has also submitted a report to *Science* on the photo-deposition of PDAMNA from solution. He also subbmitted a paper with Dr. Marcus Vlasse to *Makromolecular Chemie* on the X-ray crystal structure of the diacetylene monomer.

Since Dr. Manfred Lichtensteiger's arrival at NASA/MSFC on 15 November 1993, as Senior Scientist, his entire effort has been directed towards the implementation of his preliminary design of the first of approximately 25 ampoules to be ready for an initial GCEL test at Teledyne Brown Engineering (TBE) facilities. This ampoule was delivered ahead of schedule.

The design evolved during discussions with members of the GTE-OSRAM technical staff during a number of visits and discussions with numerous professionals in the field of Materials Science and Engineering. Some of the design concepts were adapted from the solidification experiment MA-060 which was flown during the Apollo-Soyuz mission.

It employs a modular approach, using 0.8 mm Ø platinum wire electrical feed-throughs with a compressed molybdenum foil quartz seal, cup-shaped graphite electrodes which are both mechanically and electrically connected to the feed-throughs rated at 150 W continuous power, a highly gallium-doped germanium single crystal–oriented along the <111> growth direction–machined first to approximate dimensions and then followed by chemical etching to

precise dimensions. This crystal is inserted (class A fit) into the graphite electrodes to ensure optimal electrical contact, and the whole assembly is sealed in a quartz sleeve *via* a ring seal at the end of either feed-through. Evacuation and sealing-off completes the ampoule assembly whose dimensional and electrical tolerances are prescribed by TBE.

The basic design needs only minor modifications: specifically changes to maintain concentricity, and improvements in the somewhat awkward mechanical/electrical mating of the graphite electrode to the feed-throughs.

Dr. Lichtensteiger also performed research in the following areas during this period of performance:

- Passing well-defined electrical pulses of approximately $20A/cm^2$ current density across the solid-melt interface in a growing crystal leads to localized changes in the dopant segregation behaviour at the interface.

- High quality polishing and careful etching of the crystal sectioned along the growth direction will make these changes visible by optical methods (Nomarski interference contrast). Thus, the shape of the interface, and with knowledge of the pulse repetition rate—the instantaneous microscopic growth rates can be established throughout the grown material: a fact of not only theoretical but also practical importance. When this technique is complemented by high resolution electrical measurements, which yield localized dopant concentration changes (Spreading resistance measurements), a dynamical theory of crystal growth—correlating instantaneous growth rate changes with dopant segregation behaviour—can be developed. This is the ultimate goal of this beginning investigation which has been named "IDFT" and is to be conducted during USML-2.

Ms. Elizabeth L. Forsythe continued lysozyme solubility data collection varying molarity of buffer and face growth rate data collection on 110 and 101 faces of lysozyme. She also continued crystallization studies of ovostatin and prepared a poster and a paper for ICCBM. She attended a chemical inventory training class and the hazardous waste training at NASA/MSFC Building, 4200.

Dr. Terry D. Rolin focused his support on the following activities during this reporting period:

- <u>CGF Project Science</u> - Primarily supported GCEL testing at TBE's GCEL Test Facility. This support involves monitoring the tests to insure that there is no science impacts and assisting the PI on any CGF related issues. Subsequent to each GCEL test, his services were needed to cut into the SACA, remove the ampoule and deliver it to the Principal Ivestigator. The GCEL tests thus far have involved growing crystals of HgCdTe (Rensselaer Polytechnic Institute, 2 - 14 hour tests), CdZnTe (Grumman Corporation 2- 90 hour tests) and Ga-doped Ge (Case Western Reserve University 1- 70 hour test). The latter crystal growth also included current pulse interface demarcation (CPID) which is a new added feature to TBE's GCEL furnace. To insure that the crystal exhibited interface demarcation, Frank Szofran and Dr. Rolin cut, polished, etched and analyzed the crystal. The conclusion to the analysis was that the CPID system did indeed

work for CWRU's Ga-doped Ge sample. CPID capability is a valuable asset in crystal growth since one can use the demarcation lines to determine instantaneous growth rate and, more importantly, interface shape.

In addition to supporting PI testing at the GCEL, Dr. Rolin performed some thermal modeling for the MSFC and CWRU samples. The focus of this modeling was to determine the impact of altering the furnace configuration on each PI. Final results from this modeling effort are awaiting actual test data from a differently configured furnace.

In Microgravity Science, Dr. Rolin supported the Crystal Growth and Solidification Physics Branch which also involved his research. Included in this effort was finishing a mathematical analysis aimed at determining the impact of replacing a permanent magnet with a solenoid magnet in the Magnetic Damping Furnace (MDF) at Marshall. The final report from this study is attached as Appendix 1 and represents a significant effort.

Dr. Rolin's other research efforts became two-fold this quarter, involving not only measuring the conductivity of semiconductor melts but also growing Ga-doped Ge crystals. As reported, the conductivity measuring apparatus was in its design stages. This quarter it has been built and a proof of concept test was run. The apparatus maintained structural integrity as well as vacuum pressure up to $900^\circ C$, the upper limit of the test.

Dr. Rolin has been working with Dr. Manfred Lichtensteiger to grow Ga-doped Ge crystals in TBE's GCEL furnace. This future flight effort has been labeled IDFT or Interface Demarcation Flight Test and is currently planned for the USML-2 mission. The existence of this demarcation test along with CWRU's GaAs experiment (also planned for interface demarcation) increases the chances of growing a crystal in space which will exhibit the vitally important demarcation lines.

Dr. Rolin works with Dr. Lichtensteiger in UAH's glass blower and MSFC's fabrication shop to produce the first IDFT ampoule which was delivered to Teledyne Brown Engineering on schedule. This ampoule will be the first IDFT development ampoule to be tested with a tentative test date set for January 10, 1994. To prepare for the mission, at least 20 of these ampoules will have to be assembled, tested and analyzed. This will require a significant portion of Dr. Rolin's time in order to meet the USML-2 deadline.

In support of the USML-2 mission, Mr. Rick McConnell prepared, published and distributed an updated personnel directory and the minutes of the Fourth Investigator Working Group (IWG) meeting. In support of the IML-2 mission, he performed the following activities:

- Attended status and flight operations meetings and noted action items for the mission scientist team;
- Coordinated with Boeing TV the videotaping of two experiments at the Payload Crew Training Complex (PCTC);
- Prepared mission scientist team references and documentation and participated in the first cadre simulation;
- Worked with NASA personnel to process accreditation requests for international participants; and

- Prepared, published and distributed the minutes and presentations of the seventh IWG.

2. Problems

Dr. Rolin encountered one problem. Some vacuum grease leaked onto the inner insulating spacer which subsequently blackened the spacer. A new insulating spacer is being cast for the calibration run. Also a new fixture is being designed so that the tungsten plates (current plates) can be welded to the tungsten electrodes reproducibly from test to test.

3. Activities To Be Performed

Dr. Ho plans to continue collecting data and analyzing structure interactions of various epitopes with antibodies against HIV virus and collecting data and analyzing structure interactions of various natural substrates with serum albumins.

Dr. Rolin plans include assisting the PI's, NASA, and TBE to insure that subsequent PI tests will be successful. Testing is now planned to continue through April 1994, and it is speculated that most of his CGF Project Science support time will be spent in that effort. This will involve inspecting incoming ampoules, reviewing ampoule loading procedures in the SACA's, documenting sample/SACA compatibility issues, providing assistance during GCEL testing and removing the ampoules from the SACA to deliver to the PI.

With respect to Microgravity Branch support and Dr. Rolin's research, efforts are aimed at concluding the conductivity experiments on Ga-doped Ge and InGaSb. Furthermore, Dr. Rolin and Dr. Lichstensteiger intend to deliver future IDFT ampoules to TBE to be tested in the CGF furnace. The necessary components are presently being purchased.

Dr. N. Ramachandran plans to accomplish the following tasks during the next reporting period:

1. Complete the USML-1, USMP-1 and MGMG Mission report;
2. Complete papers for SPIE conference;
3. ED 36: Data Acquisition and Instrumentation Branch;
4. Bring the 5 watt LDV setup on line and prepare for the Oxidizer Turbopump tests in early February;
5. Complete analysis on high Reynolds number effects on 5-hole and Cobra probes and hot wires;
6. Develop correction schemes to account for differences in calibration and experimental conditions;
7. Complete analysis of data obtained from wall proximity tests of 5-hole probes;
8. Follow up on the LDV measurements in the ventilated enclosure geometry and write up a technical report.

During the next quarter, Dr. Paley will continue his investigations into both solution and vapor deposition of PDAMNA thin films, with the emphasis on the solution work. In February he should know whether or not his proposal on photo-deposition of PDAMNA thin films from solution will be funded. He plans to continue the laser-deposition studies, and hopes to optimize

the technique sufficiently to construct and test some simple optical circuits for devices. He plans to do some NMR and FTIR characterizations of the chemical composition of the PDAMNA thin films.

Mr. McConnell's support of the IML-2 mission will include:

- Preparing for and participating in three simulations;
- Working with Boeing TV on the production of a mission video;
- Preparing science tracking charts;
- Attending status, flight operations and simulation meetings;
- Organizing documentation for the mission scientist team; and
- Assisting the Mission Manger in the distribution of mission brochures.

In support of the USML-2 mission his responsibilities will include organizing and distributing information concerning the Fifth Investigator Working Group meeting.

4. <u>Travel</u>

Dr. King traveled to Boulder, Colorado, to attend the Microgravity Science and Applications Science Planning Conference, September 26-29, 1993. Invoices were received during this reporting period causing a delay. He also traveled to Cleveland, Ohio, to participate in two Requirements Definition Reviews at Lewis Research Center (LeRC) for the CM-1 and TGDF Programs, October 12-15, 1993. Dr. Kings technical report is attached as Appendix 2.

Dr. Paley traveled to Toronto, Canada to participate in the joint meeting of the American Chemical Society and Optical Society of America's (ACS/OSA) entitled, "Organic Thin Films for Photonic Applications," October 2-9, 1993.

Drs. Su and Sha traveled to Nashville, TN, to visit Fisk University to attend the 1993 Symposium and technical review of the Center for Photonic Materials and Devices, October 22, 1993.

Dr. Sha traveled to Purdue University, W. Lafayette, IN, to perform viscosity measurements of HgZnTe samples in support of Dr. Alex Lehoczky's flight project, November 14-29, 1993.

Dr. Ramachandran travel to New Orleans, November 29-December 3, 1993 to present a paper entitled, "Acceleration Environment on the Space Shuttle and its Impact on Thermo-Solutal Fluid Mechanics," at the <u>ASME 114th Winter Annual Meeting</u>.

5. <u>Consulting and Workshops</u>

Dr. Julian Szekely from the Massachusetts Institute of Technology was appointed as a consultant to travel to Tokyo, Japan, to participate in the 3rd IUMRS International Conference on Advanced Materials, August 31-September 4, 1993, to give a presentation on Drop Tower Interactions with NASDA. Invoices were received during this reporting period causing a delay.

Mr. Hendrik R. Stark from the European Space Agency in The Netherlands, was retained as a consultant to travel to NASA/MSFC to attend the Joint L-1 Science Review for USML-1 and USMP-1 meeting, September 19-26, 1993. Invoices were received during this reporting period causing a delay. A summary of his activities is attached as Appendix 3.

Dr. Martin Glicksman, Director of the Microgravity Program, traveled to NASA/MSFC to participate in the IML meeting and to consult with MSA personnel, September 20-23, 1993. Invoices were received during this reporting period causing a delay.

Dr. Manfred Lichtensteiger from Woburn, MA, was appointed as a consultant to travel to Eagle-Picher Manufacturing Plant in Quapaw, Oklahoma, September 30 through October 2, 1993, to examine prints and drawings related to the Crystal Growth Facility (CGF). Dr. Lichtensteigher met with Mr. Denny W. Thomas, General Manager, and Mr. James H. Meyer, Operations Manager to discuss the general aspects of the effort. He toured the facility, quality control area, the finishing laboratory, and met with Mr. Chuck Poznich, Engineering Manager (Crystal Growth) and Dr. Jroy C. Richter, Senior Physicist to discuss in detail the quantified orientation tolerance, axial dopant level gradient, radial dopant level distribution, acceptable defect density, dimensional tolerances related to center-less grinding, and the required documentation for the individual crystals with respect to the originially grown boule.

Dr. Robert Sokolowski from Intermagnetics General Corporation in Guilderland, NY, was retained to meet with scientists of the Marshall Space Flight Center Microgravity Science and Applications Division, October 13-17, 1993.

6.   Subcontracts

The subcontract with the University of Alabama in Huntsville for contract oversight continues for Dr. James Van Alstine.

7.   Publications Submitted

Felecia L. Ewing, Elizabeth L. Forsythe, and Marc L. Pusey, "Orthorhombic Lysozyme Solubility," submitted to *Acta Crystallographica D* (meeting proceedings), 1993.

Elizabeth L. Forsythe, Felecia L. Ewing, and Marc L. Pusey, "Tetragonal Lysozyme Face Growth Rates-Revisited," submitted to *Acta Crystallographica D* (meeting proceedings), 1993.

Elizabeth L. Forsythe and Marc L. Pusey, "The Effects of Temperature and NaCl Concentration on Tetragonal Lysozyme Face Growth Rates," submitted to *J. Crystal Growth*, 1993.

D. C. Gillies, D. J. Larson, Jr., S. L. Lehoczky, F. R. Szofran, Ching-Hua Su, Yi-Gao Sha, and Helga Alexander, "Bulk Growth of II-VI Crystals in the Microgravity Environment of USML-1," *SPIE Conference Proceedings*, Vol. 2021, 10, 1993.

N. Ramachandran, S. Hudson, W. J. Bordelon, and A. Smith, "Radial and Circumferential Flow Surveys at the Inlet And Exit of the Space Shuttle Main Engine High Pressure Fuel Turbine Model," has been accepted for presentation at the 32nd AIAA Aerospace Sciences Meeting, Jan. 10-13, 1994.

Two papers co-authored with Charles Baugher entitled, "The Vibration Environment of the Space Shuttle," and "Signatures of Transient Events From the Analysis of STS Acceleration Data," have been accepted for presentation at the SPIE International Symposium, April 4-8, 1994, in Orlando, Florida.

APPENDIX 1

An Alternate Method for Magnetic Field Generation in the Magnetically Damped
Furnace (MDF)
A Preliminary Report

I. Introduction

The MDF is a specialized flight furnace unit consisting of a high temperature furnace
contained within a permanent magnet. The purpose of the magnet stems from ground
based experiments which have established that magnetic fields can be used to damp
convective flows in electrically conductive melts.[1,2] Likewise, magnetic fields should be
useful for damping g-jitter induced convection on space vehicles, an hypothesis which is
to be tested on a future flight. Although the permanent magnet is a simple solution to
providing a magnetic field, permanent magnets typically have many disadvantages
including low field intensity at "conservative" magnet weight, poor field uniformity and a
lack of active control. Electromagnets, although slightly more difficult to design, exhibit
excellent field uniformity and can provide the operator with active control (e.g., on/off
control and variable field strength). However, electromagnets also have their
shortcomings. For example, adequate cooling must be made available since the current
flow used to produce the electromagnetic field can result in significant Joule heating.
Furthermore, power constraints of manned space vehicles may limit the maximum field
intensity that can be generated. This preliminary report contains a description of a
solenoid electromagnet design and the calculations necessary to determine the impact of
substituting a permanent magnet with a solenoid electromagnet. No extensive price
evaluation is included due to the preliminary nature of this report.

II. Design

As in any space hardware design, one must operate within certain boundary
conditions to determine the optimal design parameters which accomplish the science
objectives, but do not sacrifice crew safety or other scientific experiments. Below is a list
of such conditions imposed on the design of the magnetic furnace:

A. Maximum length of magnet ---- 40.0 cm
B. Maximum weight of magnet ---- 300.0 lbs (*)
C. Maximum bore diameter ---- 20.4 cm
D. Maximum magnet diameter ---- 40.0 cm
E. Maximum power draw ---- 2.0 kW
F. Minimum field strength ---- 1000 Oe
G. Field Stability ---- 10 % (**)

[1] K. Terashima, T. Katsumata, F. Orito and T. Fukuda, Jap. J. Appl. Phys. 23 (1984) L302.
[2] C. Su, S.L. Lehockzky, F.R. Szofran, J. Crys. Growth 109 (1991) 392.

(*) Does not include weight of power supply, cooling water, insulation, etc.
(**) Represents the field "fall-off" over the inner 10 cm of the magnet

Three basic magnet designs were analyzed as substitutes for the permanent magnet. These included a Bitter disk magnet, a superconducting solenoid, and a non-superconducting solenoid. Bitter disk magnets, which are used in many high field applications, were a viable candidate owing to their large field strength and ease of cooling. However, the disk design was not chosen because driving the magnet required excessive current densities which exceeded pre-defined power constraints (see list above) were required.[3] Superconducting solenoids, capable of producing field strengths in excess of several thousand Oe, were also attractive candidates. Unfortunately, these magnets must be cooled with specific cryogen's which are not presently allowed on board a manned spacecraft. The final design consideration was a non-superconducting solenoid. Unlike the Bitter disk magnet, the non-superconducting solenoid is more efficient at lower field strengths, i.e., field strengths of one to three kOe can be produced with less power. Furthermore, the windings are not superconducting so there is no need for a liquid cryogen. Flowing water is sufficient for cooling. Based upon these factors, the non-superconducting solenoid was determined to be a workable solution.

As part of the solenoid winding design, the effects of aluminum and copper wire on design parameters were studied. Both 14 (0.1628 cm dia.) and 16 gage (.1291 cm dia.) wire diameters were studied for comparative purposes. These gage sizes are rated at a maximum current of 20 and 10 Amps for copper and 16 and 8 Amps for aluminum, respectively. These values assume that one uses a suitable electrical insulation. Both materials were chosen over other metals on the basis of workability, weight, and resistance/price per 1000 feet.

III. Calculations

The appropriate calculations to determine the field of a solenoid can be found in many undergraduate physics textbooks. However, dependence of the field on distance inside and outside the solenoid was not such a simple calculation. To find the distance dependence, one must begin with the field equations of an individual current loop and determine how the field varies with distance along the loop's central axis. An example of the loop used for the following calculations is shown in Figure 1. Using this figure, it was then assumed that the solenoid could be treated as a distribution of these current loops so that the total field represents a superposition of each individual field.

To calculate the field along the axis of a current loop the familiar Biot-Savart law was employed:

$$dB = \mu_o \, Idl \, / \, 4\pi \, r^2 \qquad\qquad 1$$

[3] D. B. Montgomery, <u>Solenoid Magnet Design. The Magnetic and Mechanical Aspects of Resistive and Superconducting Systems</u>, Wiley-Interscience, New York, 1969.

where dB is an increment of the B-field, μ_0 is the permeability of free space, I is the current, dl is the incremental change along the loop circumference and r is the distance from the periphery of the loop to the point at which the field is measured. Note that only the B-field in the z direction (z direction being along the central axis of the loop) will be maintained. The y-component of the field cancels out due to the direction of dl which leads to rotation of the vector component B_y through 360°.
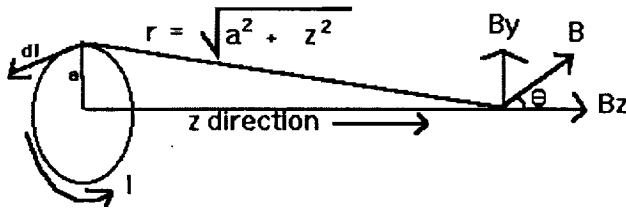

Figure 1. Magnetic field components By and Bz produced by I dl.

From the figure above, r in the Biot-Savart law was found equivalent to the hypotenuse of a right triangle so that the Biot-Savart equation was rewritten as:

$$dB = \mu_o Idl \, / \, 4\pi \; (a^2 + z^2) \qquad\qquad 2$$

The equation was simplified further by defining B in terms of its individual vector components such that:

$$\frac{dB_z}{dB} = \cos\theta \qquad\qquad 3$$

As stated before, the y component of B cancels out and was not treated in this analysis. Equation 3 was substituted into equation 2 yielding:

$$\oint dB_z = \oint \mu_o \, I \cos\theta \;\; dl \, / \, 4\,\pi \; (a^2 + z^2) \qquad\qquad 4$$

An examination of Figure 1 revealed that cos θ was equal to the loop radius divided by the hypotenuse. After integration of dB_z it was found that:

$$B_z = \mu_o I \, a \, / \, 4\pi \;(a^2 + z^2)^{3/2} \oint dl \qquad\qquad 5$$

The integral of dl around the circular loop was simply the circumference of the loop, therefore:

$$B_z = \mu_o I a^2 \, / \, 2(a^2 + z^2)^{3/2} \qquad\qquad 6$$

Equation 6 represents the equation for the field of a current carrying loop at some distance away along the central axis of the loop. This equation was the starting point for deriving the solenoid field equation.

For the field inside a solenoid, the field of Equation 6 was summed over N coils where the net solenoid field was treated as a superposition of coils. Using this treatment it was determined that the number of turns in a length dz is just (N/l)dz and thus the total current is I(N/l)dz. Equation 6 was adjusted with this new total current formula (see Equation 7) in order to determine the field intensity at various points in the solenoid.

$$dB_z = \mu_o(N/2l)Ia^2 \, dz / (a^2 + z^2)^{3/2}$$ 7

Equation 7 was then adapted by establishing a reference point, z_0, so that the field outside the solenoid could be determined:

$$dB_z = \mu_o(N/2l)Ia^2 \, dz / (a^2 + (z_o - z)^2)^{3/2}$$ 8

Integrating this equation along the length of the solenoid, i.e. from 0 to L, leads to:

$$B = \frac{\mu_o NI}{2L}\left[\frac{L - z_o}{\sqrt{(L - z_o)^2 + a^2}} + \frac{z_o}{\sqrt{z_o^2 + a^2}}\right]$$ 9

Note that this equation must obey the boundary conditions for an infinite solenoid in order to be valid. Equation 9 was checked against these conditions by assuming that L (solenoid length) is much larger than a (solenoid radius) and that $B = \mu_0 NI / L$ at the center of the solenoid and $B = \mu_0 NI / 2L$ at the ends are true. Testing Equation 9 at $z_0 = 1/2 L$ leads to:

$$B = \frac{\mu_o NI}{2L}\left[\frac{L - \frac{1}{2}L}{\sqrt{(L - \frac{1}{2}L)^2 + a^2}} + \frac{\frac{1}{2}L}{\sqrt{(\frac{1}{2}L)^2 + a^2}}\right]$$ 10

and since L>>a, the a was dropped in the denominator leading to:

$$B = \frac{\mu_o NI}{2L}\left[\frac{\frac{1}{2}L}{\sqrt{\frac{1}{4}L^2}} + \frac{\frac{1}{2}L}{\sqrt{\frac{1}{4}L^2}}\right] = \frac{\mu_o NI}{L}$$ 11

This obviously obeys the first condition. At the ends of the solenoid the following criteria were established -- $z_0 = 0$ or $z_0 = L$ depending on which end of the solenoid is of interest. Using $z_0 = 0$, one gets the expression:

$$B = \frac{\mu_o NI}{2L}\left[\frac{L}{\sqrt{L^2 + a^2}} + 0\right] = \frac{\mu_o NI}{2L} \qquad if \ L >> a$$ 12

Likewise, the same result was obtained for $z_0 = L$, thereby satisfying the second condition. Once these boundary conditions were satisfied, the equation for the solenoids B-field, Equation 9, was considered correct.

In addition to the B-field, calculations for other design parameters were considered. For example, to determine the dependence of magnet diameter on the number of turns, length and diameter of the magnet bore, the number of windings and wire diameter were considered. These variables were combined to find the integer number of windings (also known as the stack coefficient) which are built on the magnet bore:

$$n_{max} = Round(\frac{N_T d}{L}). \qquad\qquad 13$$

In this equation N_T is the total number of windings, d is the wire diameter and L is the bore length. A more beneficial way of using this equation was accomplished by defining n_{max} to be an integer and then calculating N_T. This method resulted in more meaningful data and was used in subsequent analysis.

The next critical parameter identified was the length of wire necessary to wrap the bore, hence producing a field determinable from the field equations. By analyzing the length of wire one stack at a time, an emerging pattern in the length for each turn was recognized:

$$First\ turn: \quad \frac{2\pi\ aL}{d} \qquad Second\ turn: \quad \frac{2\pi\ (a+d)L}{d}$$

$$14$$

$$Third\ turn: \quad \frac{2\pi\ (a+2d)L}{d} \qquad Fourth\ turn: \quad \frac{2\pi\ (a+3d)L}{d}$$

This pattern can be written in summation form for the total length, l_T as:

$$l_T = \sum_{n=0}^{N\,max} \frac{2\pi\ (a+nd)L}{d} = 2\pi\ Ln_{max}\frac{a}{d} + 2\pi\ L\sum_{n=1}^{N_{max}} nd \qquad\qquad 15$$

Fortunately the sum converged to $1/2\ n_{max}(n_{max}+1)$ so that Equation 15 can be rewritten as:

$$l_T = \frac{2\pi\ Ln_{max}a}{d} + \pi\ L[n_{max}(n_{max}+1)] \qquad\qquad 16$$

The important assumption for deriving this length was that each coil around the bore must be treated as a perfect circle so that the circumference can be used to obtain a length. Although this assumption will lead to an underestimate of the true length, the resulting errors will be small due to the small diameter of the wire as compared to the diameter of the loop.

The most important boundary condition for this study, critical because of its limited supply on present space vehicles, was power. Power was determined by the following equations:

$$P = I^2 R \quad where \; R = \rho \; \frac{l_T}{A} \quad and \; A = \pi \; (\frac{d}{2})^2 . \qquad\qquad 17$$

In these equations, I is the current in Amps, R the resistance in ohms, ρ is the resistivity in reciprocal ohm-cm, and A the cross-sectional area of the wire in cm^2.

IV. Results and Discussion

As mentioned previously, solenoid magnets exhibit excellent field uniformity. To demonstrate this, Equation 9 was used to calculate the field at various points inside a solenoid. To carry out the calculations a solenoid was modeled as 40 cm long with an 8 cm bore radius. The winding was assumed to be made from 14 gage copper and stacked such that the total magnet diameter was 32.3 cm The amount of power required was calculated to be 7.6 kW. As shown in Figure 2, the field falls off only 5% (i.e., from 2850 Oe to 2700 Oe) over a 20 cm span in the center of the solenoid. Notice also that the field at the ends of the solenoid falls off to about 50% of the center field strength. The fall off value is not exactly 50%, as assumed in the boundary conditions, because Figure 2 does not represent an infinite solenoid. However, Figure 2 does indicate that an aspect ratio of 5:1 (i.e., length to bore radius) is a good approximation to an infinite solenoid.

In addition to field strength, the previously derived equations for the design variables were used to analyze power versus n_{max} for a 2000 Oe field magnet. In this analysis two radii were considered, 8 and 10.2 cm, so that one could determine which radius, if not both, would satisfy the boundary conditions. For the calculations, the magnet was assumed to be 40 cm long and the choices of windings were 14 and 16 AWG copper and aluminum. The results, plotted in Figures 3 and 4, clearly illustrate that neither bore diameter can satisfy the boundary conditions. The use of aluminum, which was chosen to satisfy weight constraints, requires too much power to drive a 2000 Oe field. This is due to the larger resistivity as compared to copper. Fourteen and sixteen gage copper wire diameters, which initially were good candidates, also fail to fall within the pre-defined envelope. Large n_{max} favors the 14 gage copper when considering power only, however, a 40 cm magnet wound with 14 AWG copper to 100 n_{max} weighs more than 700 pounds.

Clearly, Figures 3 and 4 indicate that a 2000 Oe solenoid magnet driven by 2000 Watts cannot be built with the present boundary conditions. However, an examination of equations 9 and 17 reveals that B is inversely proportional to L whereas P is directly proportional to L. Therefore, one can conclude that decreasing L, while holding the other parameters fixed, should increase the field yet decrease the power. To demonstrate this, magnet length versus power using the optimal conditions from Figures 3 and 4, is plotted in Figures 5 and 6. These figures clearly demonstrate that the power goes through a

minimum at approximately 16 to 18 cm magnet length. More importantly, a field of 2000 Oe is maintained. With this observation, a question about the field homogeneity must be answered, particularly, since a 5:1 length to bore radius ratio was previously determined to be optimal. To address this question, the field strength "fall-off" over the inner 10 cm of a 16 and 18 cm long, solenoid magnet was calculated. Table's I and II show the results of these calculations and also include other calculated solenoid characteristics for comparison to the pre-defined envelope. The table's clearly reveal that no perfect solution exists, i.e., there must be a tolerance in the boundary conditions to reach an optimal solution.

V. Conclusions

In conclusion, it was determined that a non-superconducting solenoid built to the pre-defined specifications cannot provide a 2000 Oe field using less than 2000 Watts. Figure's 3-6 as well as Table's I and II clearly prove this point. Furthermore, it can be concluded that the 20.4 cm bore magnet is disadvantageous in that the necessary power to drive this magnet severely exceeds the boundary conditions. This is true even under optimized conditions of length, field and stacking coefficient. However, a magnet can be built which provides 2000 Oe utilizing 2000 Watts if a compromise between the boundary envelope and the actual solenoid parameters can be reached. An analysis of Figure's 3-6 and Table's I and II renders that the most optimal situation is a 16 cm long magnet composed of 16 AWG Cu wire that is wound to a stacking coefficient of 100. Although this results in a magnet diameter of 41.8 cm, the diameter is less than an inch beyond the boundary condition and should not be a serious design problem. This magnet can produce a field of 2000 Oe with 1958 Watts and weighs less than 300 lbs. The only parameters which are out of specification are the diameter at 41.8 cm and the field fall-off of 15%.

Finally, it must be restated that these calculations are based solely on a hypothetical magnet alone. No considerations of power supply and coolant weight or shape have been made due to the preliminary nature of this report. In addition, the actual build up of a solenoid magnet by wrapping with wire is not a perfect process and could invalidate the calculations of wire length and magnet diameter. These factors will most definitely add to the non-superconducting solenoid list of disadvantages.
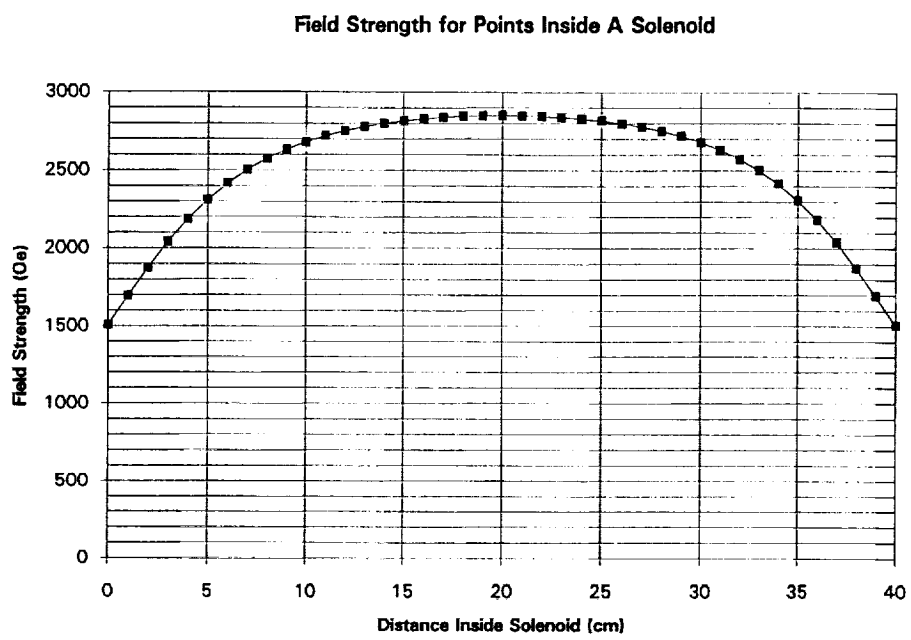
Field Strength for Points Inside A Solenoid

Figure 2 . Magnetic field strength for various points inside a solenoid.
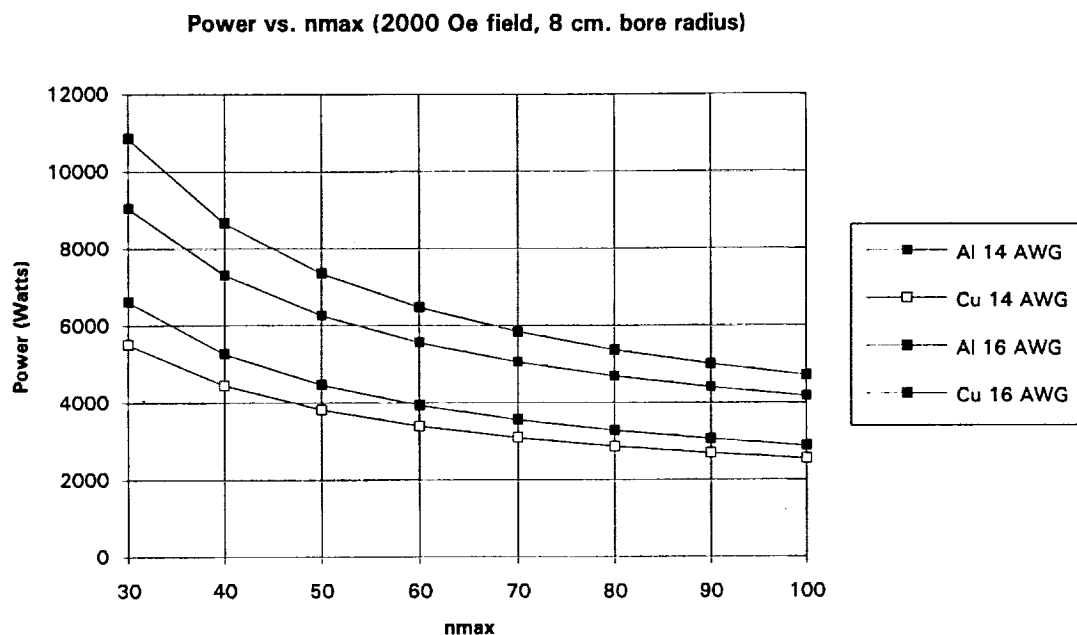
Power vs. nmax (2000 Oe field, 8 cm. bore radius)

Figure 3. Power vs. the stacking coefficient, n_{max}, for a 2000 Oe field using 14 and 16 gage Al and Cu wire. The bore diameter was assumed to be 16 cm
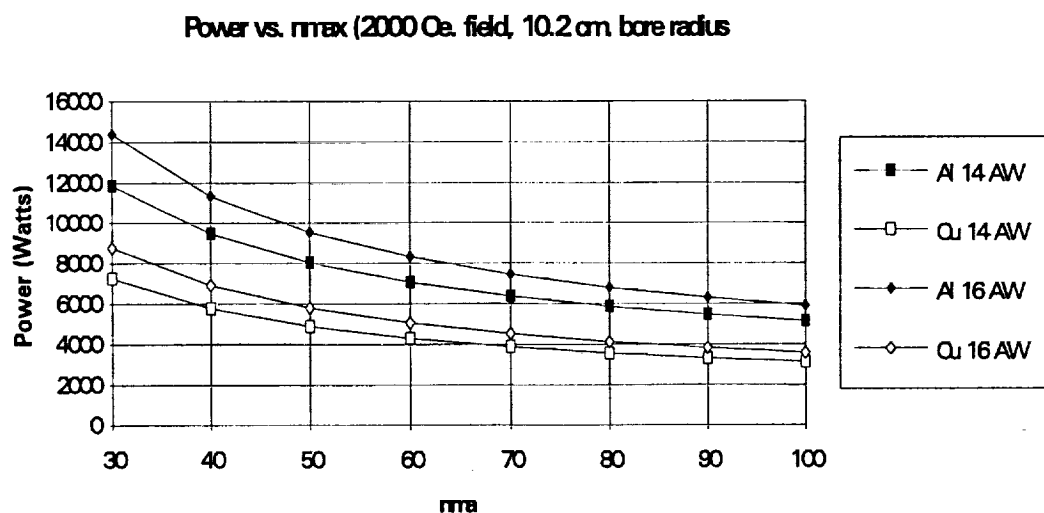
Power vs. nmax (2000 Oe. field, 10.2 cm bore radius

Figure 4. Power vs. the stacking coefficient, n_{max}, for a 2000 Oe field using 14 and 16 gage Al and Cu wire. The bore diameter is assumed to be 20.4 cm
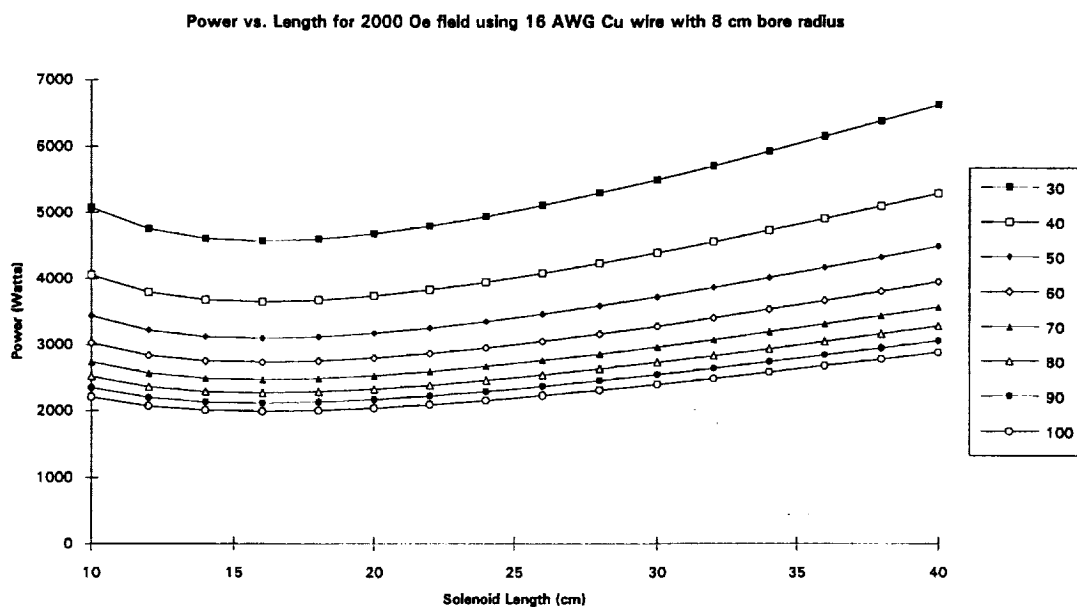
Figure 5. Power vs. length for a 2000 Oe magnet with an 8 cm bore radius and wound with 16 AWG copper.
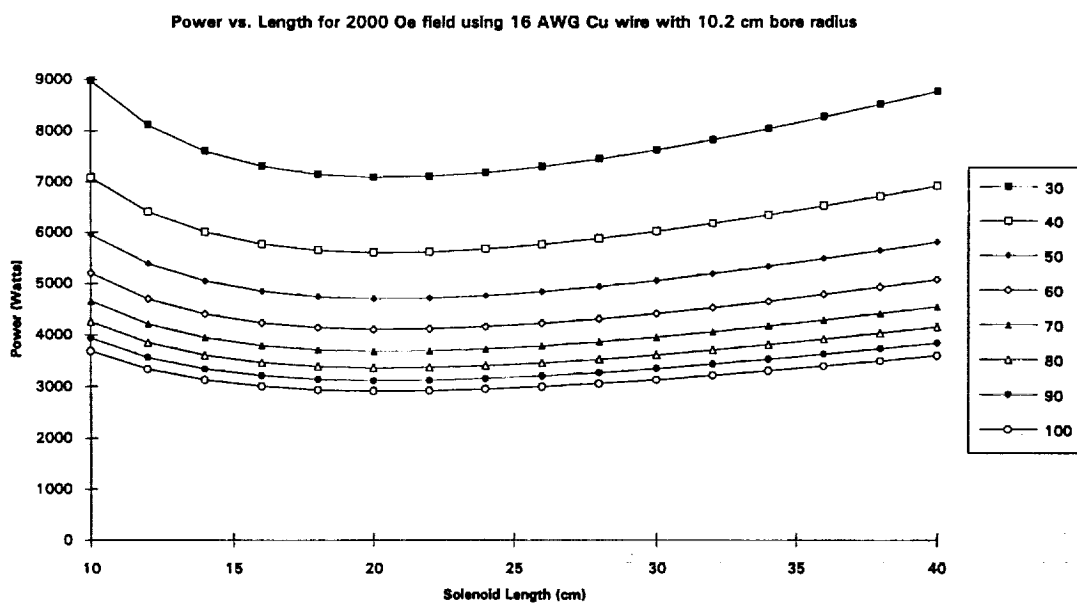

Figure 6. Power vs. length for a 2000 Oe magnet with a 10.2 cm bore radius and wound with 16 AWG copper.

Table I. Boundary condition comparison for two solenoid magnets with $n_{max} = 90$.

	Boundary Conditions	16 cm long magnet	18 cm long magnet
Magnet Length	40 cm	16 cm	18 cm
Magnet Weight*	300 lbs.	249 lbs.	281 lbs.
Bore diameter	20.4 cm max.	16 cm	16 cm
Magnet diameter	40 cm	39.2 cm	39.2 cm
Power	2000 W	2078 W	2093 W
Field Strength	2000 Oe	2000 Oe	2000 Oe
Field stability**	10%	15%	12%

Table II. Boundary condition comparison for two solenoid magnets with $n_{max} = 100$.

	Boundary Conditions	16 cm long magnet	18 cm long magnet
Magnet Length	40 cm	16 cm	18 cm
Magnet Weight*	300 lbs.	290 lbs.	326 lbs
Bore diameter	20.4 cm max	16 cm	16 cm
Magnet diameter	40 cm	41.8 cm	41.8 cm
Power	2000 W	1958 W	1971 W
Field Strength	2000 Oe	2000 Oe	2000 Oe
Field stability**	10%	15%	12%

*Earth pounds
**Field stability represents the percentage "fall-off" of the field over the central 10 cm of the magnet.

REFERENCES:

APPENDIX 2

October 1, 1993

Dr. James Van Alstine
Universities Space Research Association
4950 Corporate Drive, Suite 100
Huntsville, AL 35806

Dear Dr. Van Alstine:

This letter constitutes a brief description of my activities during the month of September, 1993 as a Visiting Senior Scientist in the Combustion Program of the Microgravity Science and Application Division at NASA Headquarters:

(1)   Continued work on Science Plan Appendix for the Combustion Program.

(2)   Collected and read Science Requirements Documents for two RDR's to be held in October (CM-1 and Turbulent Gas Jet Diffusion Flames). Continued preparations for those reviews.

(3)   Finished draft of Science Review presentation (1-hour) for Harry Holloway (Associate Administrator for OLMSA) and gave it to Roger Crouch for review.

(4)   Received, logged in, and divided into categories and subcategories 99 proposals in response to Microgravity Combustion NRA. Began reading them and choosing panelists for peer review. I will probably go with three panels, one for proposals in the area of gas-phase combustion, one for droplets, sprays, particles, and dust clouds, and one for surface combustion, smoldering combustion, and combustion synthesis.

(5)   Participated in USML-2 Glovebox Review, held at Headquarters on Sept.9-10.

(6)   Took part in MSAD Science Branch Planning Meeting in Boulder, CO on September 26-29.

(7)   Prepared input for Steve Fogleman and Howard Holloway describing how our activities might be useful to the automotive industry for presentation by them to an automotive society meeting.

I hope this is a satisfactory description of my activities during the past month with NASA. As I indicated earlier, please don't hesitate to supply criticisms if you would like me to change the format of these reports.

Very truly yours,

Merrill K. King

cc: Dr. Sandor Lehoczky
      NASA ES75
      Marshall Space Flight Center
      Huntsville, AL 35812

November 1, 1993

Dr. James Van Alstine
Universities Space Research Association
4950 Corporate Drive, Suite 100
Huntsville, AL 35806

Dear Dr. Van Alstine:

This letter constitutes a brief description of my activities during the month of October, 1993 as a Visiting Senior Scientist in the Combustion Program of the Microgravity Science and Application Division at NASA Headquarters:

(1)   Circulated draft of Science Plan Appendix for the Combustion Program to various people for comments.

(2)   Participated in Requirements Definition Review for the Turbulent GasJet Diffusion Flames (TGDF) Program (PI--Yousef Bahadori) at LeRC on October 12. Our tentative conclusion is that the project requires more work before moving into the Flight Development stage.

(3)   Participated in Requirements Definition Review for the Combustion Module-1 Program, which involves two sets of experiments and PIs: (1) Structure of Flameballs at Low Lewis Numbers (SOFBALL), Paul Ronney; and, (2) Laminar Soot Processes (LSP), Gerry Faeth, on October 13, 14, and 15. This was a very successful review, and it is anticipated that the program will be authorized to proceed into the Flight Development stage after proper processing of the committee reports/paperwork.

(4)   Read the 98 proposals received in response to the Microgravity Combustion NRA (previously reported 99 shrank to 98 since two were the same proposal as submitted by co-PI's from two institutions) and assigned them preliminary ratings. Divided them into three major categories for panel review.

(5)   Completed setting up review panels for two of the three proposal groups and distributed proposals to the reviewers. The first panel,

consisting of eleven panelists and covering proposals in the gas flames area, will meet at Headquarters on Nov. 8 and 9, while the second panel, consisting of nine panelists and covering proposals in the area of droplets, sprays, particles, and dust clouds will meet on Dec. 2 and 3. Eight reviewers have been selected for a third panel covering surface combustion, smoldering, and combustion synthesis, which will meet on Dec. 13 and 14; it is expected that two more panelists will be selected to fill out this panel within the next day or two.

I hope this is a satisfactory description of my activities during the past month with NASA. As always, please don't hesitate to supply criticisms if you would like me to change the format of these reports.

Very truly yours,

Merrill K. King

cc: Dr. Sandor Lehoczky
        NASA ES75
        Marshall Space Flight Center
        Huntsville, AL 35812

December 1, 1993

Dr. James Van Alstine
Universities Space Research Association
4950 Corporate Drive, Suite 100
Huntsville, AL 35806

Dear Dr. Van Alstine:

This letter constitutes a brief description of my activities during the month of November, 1993 as a Visiting Senior Scientist in the Combustion Program of the Microgravity Science and Application Division at NASA Headquarters:

(1)　Modified Science Plan Appendix for Microgravity Combustion Program to reflect comments received from Gerry Faeth, Howard Ross, and Roger Crouch. Also generated two summary tables to be included in main body of Science Plan being generated by Dr. Crouch. Gave copies to him and to Bob Rhome for further review.

(2)　Prepared an input of approximately 1500 words on what has been done in the Microgravity Combustion Program during 1993 for the Annual Report.

(3)　Prepared packages for the Project Scientists (at LeRC) regarding what needs to be done to finalize the Science Requiremqnts Documents for the Laminar Soot Processes (LSP) and Structure of Flameballs at Low Lewis Numbers (SOFBALL) programs based on results of the recent CM-1 RDR, particularly inputs from the various review panels involved.

(4)　Drafted letters for Gerry Faeth (LSP) and Paul Ronney (SOFBALL) regarding their approvals (upcoming shortly) to proceed to Flight Development on their projects.

(5)　Conducted first panel review of proposals received in response to the Combustion NRA on Nov. 8 and 9. Thirty-six proposals in the gaseous flames area were reviewed by this panel, with seven of them being rated as Highly Qualified and nineteen as Qualified. Currently in the final stages of preparation for the second panel

review, to held Dec. 2 and 3, in which thirty proposals in the areas of droplet/spray combustion, solid particle combustion, and dust cloud combustion will be evaluated.

(6)   Reviewed three papers for scientific journals.

(7)   Had survey paper entitled "Erosive Burning of Solid Propellants" published by the Journal of Propulsion and Power in their November/December, 1993 issue.

I hope this is a satisfactory description of my activities during the past month with NASA. As always, please don't hesitate to supply criticisms if you would like me to change the format of these reports.

Very truly yours,

Merrill K. King

cc: Dr. Sandor Lehoczky
        NASA ES75
        Marshall Space Flight Center
        Huntsville, AL 35812

APPENDIX 3

esa european space agency

estec european space research and technology centre

ANNEX - ACTIVITIES AT NASA MSFC

In the frame of the Joint L+1 Science Review for USML-1 and USMP-1 and the Microgravity Measurement Group Meeting, two papers have been presented as following:

- **ESA activities on Microgravity and Microdynamics including the presentation of the Spacelab D-2 "MMA Transfer Function Experiment"**

  The paper provides an overview on the ESA microgravity and microdynamics activities in the field and applications of ongoing projects and programmes. A review is given on microgravity payload sensitivities, disturbance sources, micropointing stability requirements of satellites and scientific experiments. Microdynamics control approaches, plans and philosophies are presented which are employed in various project and programmes. The paper comprises in addition the description of various supporting technology tasks which are performed in the framework of ESA R&D activities which shall provide the scientific projects and programmes with adequate solutions.

- **EURECA Microgravity Environment - Preliminary Flight Data**

  This paper summarizes a preliminary review of the residual accelerations as measured during the first mission period of EURECA, the European Retrievable Carrier, between the 07.08.92 and the 1.10.92 in correlation with the previous analysis and ground test results, as well as some later data. The on-board Microgravity Measurement Subsystem (MMS) detected the residual accelerations after command from ESOC, Darmstadt. This review is namely based on a set of 906 acceleration measurements during the initial period, with a duration of 3,167 minutes and in some cased up to 657,6 minutes. Additional calculations on the effect of gravity gradient and atmospheric drag are included. The paper presents these findings and the conclusion that the desire design goal for the microgravity quality on EURECA was met.

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Neutral Aeronautics and Space Administration

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15. Supplementary Notes

16. Abstract

Contract NAS8-38785, Microgravity Experimental and Theoretical Research, is a project involving a large number of individual research programs related to:

Determination of the structure of human serum albumin and other biomedically important proteins; Analysis of thermodynamic properties of various proteins and models of protein nucleation; Development of experimental techniques for the growth of protein crystals in space; Study of the physics of electrical double layers in the mechanics of liquid interfaces; Computational analysis of vapor crystal growth processes in microgravity; Analysis of the influence of magnetic fields in damping residual flows in directional solidification processes; Crystal growth and characterization of II-VI semiconductor alloys; Production of thin films for nonlinear optics.

It is not intended that the programs will be necessarily limited to this set at any one time. The visiting scientists accomplishing these programs shall serve on-site at MSFC to take advantage of existing laboratory facilities and the daily opportunities for technical communications with various senior scientists.

For more specific details regarding program activities, please contact: Dr. Martin Glicksman, Director, (518)276-6721; Dr. Robert Snyder, (205)544-7805; Dr. James Van Alstine, On-Site Program Director, (2205)544-7820.

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